THE RHEOLOGY OF THE BLOOD

IV. The Fluidity of Whole Blood at 37°C.*

By EUGENE C. BINGHAM and RAYMOND R. ROEPKE

(*From the Department of Chemistry, Lafayette College, Easton*)

(Received for publication, June 13, 1944)

The fluidity of blood serum and of fibrinogen solutions has been briefly referred to (1*a*). We will now consider a few data on the fluidity of whole blood of persons of different age and sex, at various times of day and under different conditions of health, with different nourishment and exercise in order to have in mind the conditions that affect the property. We will choose for our first consideration data obtained with the Hess viscometer by a few workers who accumulated a considerable mass of data each. We assume the fluidity of water at 37° to be 144 rhes.

Since the fluidity of the whole blood of healthy adult males is lower than that of youths or of females and less changeable than that of diseased persons, we will first (Table I) study the data for forty-eight healthy males who were over 14 years of age studied by Blunschy (2) in 1908. They are arranged in the order of increasing hemoglobin percentage content of the blood, the ages also being given. It is observed that the fluidity increases with the hemoglobin content and we have fitted the following formula to the data:

$$\phi = 53 - 0.24\,H \qquad (1)$$

where H is the hemoglobin content by the Sahli method, 16.1 gm. per 100 gm. of blood being considered normal, and 53 is the fluidity which the blood would have if the hemoglobin content were reduced to zero; *i.e.*, plasma. On the other hand, the equation points to a hemoglobin content of 220 for a fluidity of zero, provided of course that the equation is valid for extrapolation. The average deviation between the observed and calculated values is 3.3 per cent. Since the hemoglobin content is obviously not correct to two significant figures, this is perhaps all that can be expected. Assuming the average hemoglobin content of the healthy adult male to be $90_{\pm 7}$, the normal fluidity of this individual should be 31.4 rhes. Dividing the cases in Table I into four groups of twelve, it may be observed that in the first group the average age is 24 years, in the second 34, in the third 31, and in the fourth 30. It appears that those of this first group are low in hemoglobin content and somewhat low in age, showing a connection between hemoglobin content and age, which is more marked as the age is lowered; nevertheless the formula for calculating the fluidity applies

* Supported by a grant from the John and Mary R. Markle Foundation.

TABLE I

The Relation between the Fluidity and the Hemoglobin Content of the Blood of Healthy Males above 14 Years of Age

After Blunschy (2).

Age	ϕ	H obs.	ϕ calc.	Deviation
15	37.2	70	36.2	−1.0
16	35.8	72	35.7	−0.1
32	33.6	75	35.0	+1.4
16	35.1	80	33.8	−1.3
32	34.5	80	33.8	−0.7
20	34.0	80	33.8	−0.2
16	33.7	80	33.8	+0.1
16	33.3	80	33.8	+0.5
43	33.1	80	33.8	+0.7
21	31.9	80	33.8	+1.9
20.5	32.7	80	33.8	+1.1
38	32.7	82	33.3	+0.6
58	31.8	82	33.3	+1.5
23	32.9	85	32.6	−0.3
22	32.5	85	32.6	+0.1
20	32.4	85	32.6	+0.2
63	32.2	85	32.6	+0.4
20	32.2	85	32.6	+0.4
27	32.1	85	32.6	+0.5
33	32.1	85	32.6	+0.5
33	31.9	85	32.6	+0.7
23	31.7	90	31.4	−0.3
25	31.6	90	31.4	−0.2
65	31.2	90	31.4	+0.2
19	31.1	90	31.4	+0.3
18	31.0	90	31.4	+0.4
21	31.0	90	31.4	+0.4
21	30.7	90	31.4	+0.7
28	30.7	90	31.4	+0.7
33.5	30.6	90	31.4	+0.8
56	30.2	90	31.4	+1.2
32	30.0	90	31.4	+1.4
60	30.0	90	31.4	+1.4
40	31.0	93	31.7	−0.3
29	31.6	95	30.2	−1.4
22	31.3	95	30.2	−1.1
31	30.8	95	30.2	−0.6
21	30.7	95	30.2	−0.5
30	30.0	95	30.2	+0.2
21	29.5	100	29.0	−0.5
27	29.1	100	29.0	−0.1
29	28.8	100	29.0	+0.2
27.5	27.4	100	29.0	+1.6
43	29.7	105	27.8	−1.9
24	27.9	110	26.6	−1.3
30	25.6	110	26.6	+1.0
37	25.5	110	26.6	+1.1
42	24.1	110	26.6	+2.5

well, showing that the variation in the hemoglobin percentage may account for almost the entire changes in fluidity encountered in healthy adult males.

Youths

Blunschy (2) studied seven cases of healthy males below 14 years of age. The fluidity in all cases is much higher, 1.2 rhes, than for adults but the hemoglobin content is also uniformly lower, although not quite enough lower to account for all of the elevation of the fluidity. In all except one case, as shown in Table II, the calculated fluidity is lower than the observed, the average deviation being 1.0 rhes but without any distinct trend.

Schukowa-Florensowa (3) reported the average viscosities of normal healthy children of different ages. The percentages of hemoglobin were not reported,

TABLE II

The Relation between the Fluidity and the Hemoglobin Content of the Blood of Healthy Males below 14 Years of Age

Age	ϕ	H obs.	ϕ calc. / Equation (1)	Deviation + 1.2
8	37.6	68	36.7	+0.3
6	39.9	70	36.2	−2.5
4	37.6	70	36.2	−0.2
6	36.2	70	36.2	+1.2
12	35.9	70	36.2	+1.5
6	36.7	72	35.7	+0.2
5	36.9	75	35.0	−0.7
Average				1.0

so that the above formula cannot be applied to them. The fluidities, however, are given in Table III since they do prove that the fluidity of the blood of youths falls nearly linearly from the earliest years, according to the formula

$$\phi = 47.3 - 0.48\,y \tag{2}$$

where y is the age in years. If the high fluidity in these early years were entirely to be ascribed to low percentage of hemoglobin in the blood, the hemoglobin could be calculated also by the formula (1), as given in the fifth column of Table III and it would show a nearly steady rise from 1 year on.

It is important to get these data for hemoglobin. According to Mayers (4), the amount of hemoglobin in the blood of youths increases from the age of 1 year to 16 when it becomes constant and remains so until about 75 years of age. But according to him, up to 1 year the hemoglobin decreases steadily and rapidly from birth.

Women and Girls

The data of Blunschy for the fluidity of the whole blood of healthy women and girls given in Table IV are confined to sixteen cases. The observed fluidity is on the average of 0.7_6 rhes higher than the value calculated by equation (1) for adult men. This small difference may be experimental error but we will regard it. The average woman has a blood with a hemoglobin content $78_{\pm 8}$ which would correspond to a fluidity for males of 34.3 rhes. If we increase this by 0.7_6, we arrive at the expected average for women of 35.1 rhes, to be compared with the expected average for men of 31.4 rhes. This large difference

TABLE III

The Fluidity of the Whole Blood of Healthy Children of Various Ages

After Schukowa-Florensowa (3).

Age	ϕ obs.	ϕ calc. Equation (2)	Deviation	H calc. Equation (1)
0.6	48.0	47.0	−1.0	——
1	45.6	46.8	+1.2	29.1
2	45.9	46.3	+0.4	27.8
4	45.3	45.4	+0.1	30.3
5	45.5	44.9	−0.6	27.8
6	44.9	44.4	−0.5	32.0
7	43.3	43.9	+0.6	38.7
8	43.5	43.5	0.0	37.9
9	43.2	43.0	−0.2	39.2
10	43.9	42.5	−0.4	40.4
11	42.2	42.0	−0.2	44.2
12	39.8	41.5	+1.7	53.4
13.5	41.8	40.8	−1.0	45.0
15.5	39.5	40.0	+0.5	54.7

is due to the much lower hemoglobin content of 78 in the blood of the women tested. This difference between the two sexes accords with general experience. In the last column of Table IV, there is given the deviation as a correction for sex.

The Serum and Plasma

It is clear that the hemoglobin content of the blood of healthy persons varies widely, irrespective of age or sex and it has such an important effect that no study of the rheology of the blood can neglect it; however, that does not mean that the shape and number of the erythrocytes is not important or that the leucocytes are without rheological effect. The question naturally suggests itself as to whether the effect of the variation in blood cells should not be eliminated for comparative purposes by reducing the blood to a *standard condition* of either a normal number of blood cells or perhaps still better to a plasma without blood cells. Important as are the blood cells, the fluidities of the serum and plasma are important and they can be determined with greater ease and precision than can that of the whole blood. The measurement of the fluidity of the whole blood would perhaps best be used to determine the hemoglobin or, more exactly, the rheological constant of the red cells. It is often stated that the viscosity of the serum and plasma vary relatively little. This statement is worthy of examination because as a result of the digestive processes,

TABLE IV

The Relation between the Fluidity and the Hemoglobin Content of the Blood of Healthy Women and Girls

After Blunschy (2).

Age	ϕ obs.	H obs.	ϕ calc. Equation (1)	Deviation
49	43.6	55	39.8	−3.8
6.5	39.8	60	38.6	−1.2
5.5	38.7	68	36.7	−2.0
20.5	37.9	70	36.2	−1.7
21	36.9	70	36.2	−0.7
17	35.1	75	35.0	−0.1
32	34.7	80	33.8	−0.9
32	34.3	80	33.8	−0.5
44	31.4	80	33.8	+2.4
20	34.0	85	32.6	−1.4
55	32.7	85	32.6	−0.1
21	33.2	85	32.6	−0.6
40	33.0	85	32.6	−0.4
40	32.4	85	32.6	+0.2
31	32.7	90	31.4	−1.3
65	31.2	90	31.4	+0.2
Average				−1.1

water and food are being taken into the blood stream at varying rates. Thus salts, both inorganic and organic, glucose, fats, and urea are present together with considerable amounts of proteins. These last are by far the most important in lowering the fluidity, the most important being the albumin and globulin (8.2 per cent), although the smaller percentage of fibrinogen (0.8 per cent) is relatively even more important. Table V after Bolle (5) shows that the plasma containing the fibrinogen, invariably has a lower fluidity than the serum. The percentage of dry solids in the serum and in the plasma is given in the third and fourth columns. These are to be corrected for salts, etc. In the ten individuals who were tested, the serum had an average fluidity of 86 rhes and the plasma a fluidity of 70 rhes. The difference of 16 rhes is due to the fibrinogen, which, however, shows a wide variation of from 10 to 20 rhes which is nearly 30 per cent.

The ratio of albumin to globulin in the serum is regarded as of importance, and it shows wide variation in different individuals; the average ratio is about 62 to 38 which is roughly 5 to 3. It is thus possible to explain the wide variations in the fluidity of serum and plasma in Table V.

Starting with water which has a fluidity of 144 rhes at 37° the salts lower the fluidity by less than 1.5 rhes, the albumin and globulin together may lower it by 58 rhes, and the fibrinogen by an additional 16 rhes. Since the fluidity of the whole blood of the healthy adult male is about 31.5 rhes, it is evident that the

TABLE V

The Fluidities of the Serum and Plasma of Various Individuals, the Percentage of Dry Residue, and the Kjeldahl Nitrogen

After Bolle (5).

Fluidity		Dry residue		Kjeldahl nitrogen	
Serum	Plasma	Serum	Plasma	Serum	Plasma
96	80	9.92	10.95	1.092	1.162
85	72	9.704	10.33	1.083	1.218
90	80	8.27	8.47	1.22	1.24
85	72	10.51	—	1.171	1.265
88	72	10.04	11.22	1.157	1.288
85	72	9.87	10.92	1.30	1.33
82	65	10.89	13.46	1.273	1.358
90	69	10.01	11.48	1.269	1.372
80	60	11.58	13.42	1.279	1.395
85	63	11.92	13.02	1.220	1.407

actual lowering of the fluidity by the salts and proteins (73.5) is very much more than the lowering due to the blood cells (39 rhes). This is a very impressive fact because the blood cells make up 30 per cent of the volume of the blood. The erythrocytes must therefore possess a rather high mobility in their interior and rheologically they must be regarded as almost totally different from solid particles in suspension, perhaps more like an emulsion with the internal phase having high fluidity. This is the more remarkable since the red corpuscle is 32 per cent by weight hemoglobin which is said to be not in true solution. The flexibility of the red corpuscle is readily observed, but we are not aware that it has been measured. Also data seem to be lacking on the consistency of the contents of the corpuscle. It is well known that the organism is capable of adjusting the ratio of albumin to globulin within the body and thereby rather quickly affecting the fluidity of the blood while maintaining the water content constant. Reiss (6) showed that the proteins can be estimated by means of the refractometer. Schorer (7) showed that globulin has a higher refractive index than albumin, and suggested a method for estimating their relative amounts. Heyder (8), at the suggestion of Nägeli (9), experimented with concentrations of these two proteins, approximating those found in the blood

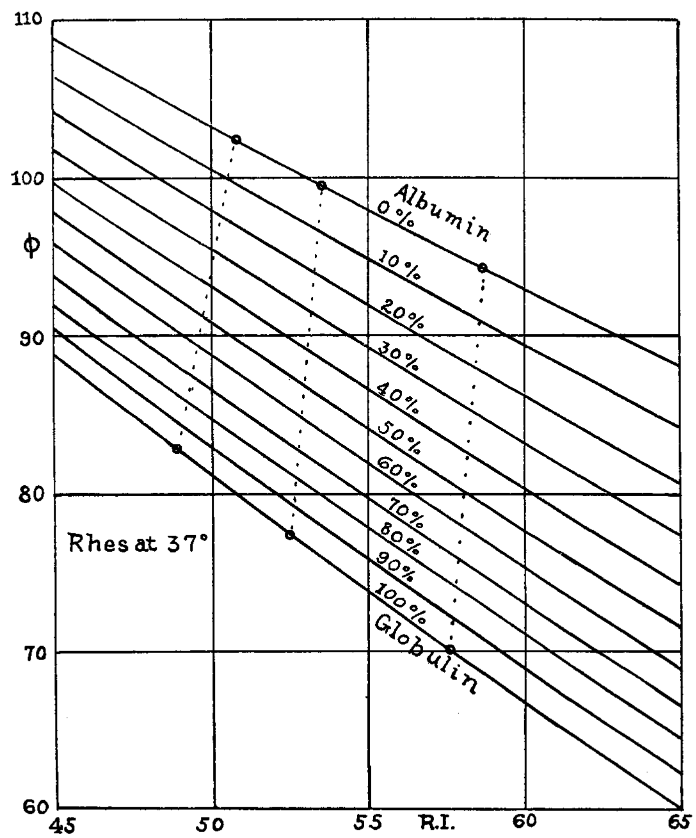

FIG. 1

serum; *viz.*, 6, 7, and 8 per cent. Nägeli constructed a family of curves, R. I. *vs.* percentage of globulin and also relative viscosity *vs.* percentage of globulin. The former were nearly linear while the latter were strongly curved. It is of interest to note that on plotting the fluidity *vs.* percentage of globulin, the curves are nearly linear, as are also the family of curves of fluidity *vs.* R. I. as shown in Fig. 1. From these data of Heyder we obtain as the concentration for zero fluidity 15.1 per cent in the case of globulin and 20.4 per cent in the case of albumin.

TABLE VI

The Relation Between the Fluidity and the Hemoglobin Content of Diseased Persons, of Various Ages and Both Sexes

After Blunschy (2).

Age	$\Phi_{obs.}$	H	$\Phi_{calc.}$	Deviation	Disease
59	52.4	30	45.8	−6	Ventriculitis
50	49.6	30	45.8	−4	Pernicious anemia
54	39.8	30	45.8	+7	Pleur. mitral insufficiency
53	58.8	37	43.9	−15	Ventriculitis
42	36.9	53	40.3	+3	Pulmonary tuberculosis
20.5	39.4	60	38.6	−1	Chlorose
15.5	33.2	60	38.6	+6	Mitral insufficiency with stenosis
28	43.3	65	37.4	−6	Pregnancy
22	39.5	65	37.4	−2	Chlorose
26	38.4	70	36.2	−2	Pregnancy
48	35.6	70	36.2	0	Bronchitis
66	33.9	70	36.2	+2	Mitral insufficiency
68	31.2	70	36.2	+5	Bronchitis
37	29.4	70	36.2	+7	Mitral stenosis
54	28.2	70	36.2	+8	Bronchitis
63	28.0	70	36.2	+8	Bronchitis
63	25.9	70	36.2	+10	Pneumonia croupous
50	35.6	75	35.0	−1	Bronchitis
19	32.5	75	35.0	+2	Cyanosis, congenital
28	32.3	75	35.0	+3	Mitral stenosis
65	31.5	75	35.0	+3	Mitral insufficiency
58	30.0	75	35.0	+5	Laryngitis
66	29.6	75	35.0	+5	Myocarditis
42	29.0	75	35.0	+6	Myocarditis
20	26.7	75	35.0	+8	Bronchitis acute
82	34.7	77	34.7	0	Arteriosclerosis
39	34.1	80	34.2	0	Nephritis
59	31.8	80	34.2	+2	Bronchitis
44	31.3	80	34.2	+3	Basedow's disease
68	31.0	80	34.2	+3	Myocarditis
49	30.8	80	34.2	+3	Mitral stenosis
20	28.5	80	34.2	+5	Pulmonary tuberculosis
30	28.4	80	34.2	+6	Basedow's disease
49	28.0	80	34.2	+6	Bronchitis
63	27.5	80	34.2	+6	Mitral stenosis
65	24.4	80	34.2	+10	Bronchitis
58	32.0	82	33.3	+1	Arteriosclerosis
47	31.0	82	33.3	+2	Diabetes, 3 per cent glucose
66	36.3	83	33.1	−3	Nephritis, 1 per cent albumin
26	30.5	85	32.6	+2	Syphilis II
64	28.2	85	32.6	+4	Paralysis agitans myocardial insufficiency
58	26.0	85	32.6	+7	Bronchitis
63	25.1	85	32.6	+8	Bronchitis
9	34.3	90	31.4	−3	Pulmonary stenosis
34	28.5	90	31.4	+3	Sepsis
62	26.5	90	31.4	+5	Bronchitis
42	25.3	90	31.4	+5	Syphilis II
45.5	24.6	90	31.4	+7	Bronchitis
7.5	17.3	115	25.2	+8	Pulmonary stenosis
8	11.6	140	19.4	+8	Pulmonary stenosis

Clinical Observations

The relation between fluidity and hemoglobin content in equation (1), appears to make it possible to compare samples of the whole blood of healthy persons above 14 years and expect concordance of about 3 per cent. Blunschy

TABLE VII

The Relation between the Fluidity and the Hemoglobin Content of Diseased Persons, of Various Ages and Both Sexes but Neither Stated

After Bolle.

Φ obs.	H	Φ calc.	Deviation	Disease
55	7	51	−4	Cancer of uterus
72	15	49	−33	Pernicious anemia
60	20	48	−12	Severe anemia
63	20	48	−15	Severe anemia
63	28	46	−15	Anemia after confinement
45	37	44	−1	Tuberculosis of lungs
40	40	43	+3	Pernicious anemia
50	40	43	−7	Anemia after confinement
42	45	42	0	Typhus
41	45	42	+1	Angina
34	50	41	+7	Arthritis gonorrhea
37	52	40	+3	Neurasthenia
37	55	40	+3	Diabetes
40	55	40	0	Pleurisy
42	55	40	−2	Sepsis after confinement
41	55	40	−1	Myocarditis
44	58	39	−5	Chlorosis
36	60	39	+3	Tuberculosis of lungs
37	60	39	+2	Tuberculosis of lungs
40	62	38	−2	Tuberculosis of lungs
31	70	36	+5	Neurasthenia
34	70	36	+2	Neurasthenia
37	70	36	−1	Tuberculosis of lungs
34	72	36	+2	Healthy man
37	75	35	−2	Ventricular ulcer
39	75	35	−4	Rheumatism of joints
41	75	35	−6	Parametritis
40	75	35	−5	Syphilis III
34	80	34	0	Healthy man
33	80	34	+1	Healthy man

has given data for fifty diseased persons and Bolle for thirty more, giving the ailment as well as the fluidity and hemoglobin content. Three persons on Bolle's list are put down as healthy and serve as norms to compare with the previous list. Blunschy's data (Table VI) show observed fluidities which are

13 per cent below the average found for healthy persons, but this figure is of little or no importance because the fluidity was found in many cases to be higher than the expected value. It is concluded that disease may affect the validity of the formula, but the effect is dependent upon the nature of the disease. Blunschy cites cases of polycythemia with a low fluidity. No. 1, a boy of 8, red cell count 9,600,000 and fluidity 11.6 rhes; No. 2, a boy of 8.5, with red cell count of 6,970,000, fluidity 17.2 rhes; and No. 3, a boy of 9, with a red cell count of 4,680,000, fluidity 35.5. All three walked up two flights of ten steps and down again from six to ten times after which the fluidity of the blood was found to be 10.6, 17.0, and 25.9 rhes respectively. There was in each case a loss in fluidity presumably due to the effect of carbon dioxide in swelling the erythrocytes. But the inhalation of 25 liters of oxygen caused the fluidity to rise to 12.4 rhes with No. 1 and to 18.3 rhes with No. 2. It is noted that the loss in fluidity by No. 3 in his sudden and severe exertion was 22 per cent. Bolle's data in Table VII give cases of cancer and anemia in which the fluidity of the blood is considerably greater than the calculated value. The average percentage deviation between the observed and calculated values has risen from 3.3 to 13.1 per cent, but even with diseased persons there is evidence of the predominating effect of the hemoglobin content, the data being arranged in the order of their increasing observed value. The increased deviation is proof that other factors than the hemoglobin content must be considered. The three boys referred to, indicate that the condition of aeration of the blood is important. It is therefore not surprising to find the fluidity lower than the expected values in bronchitis, pneumonia, and tuberculosis. It is noted that in a case with 3 per cent of glucose (Table VI) the effect on the fluidity is scarcely noticeable.

Time of Day, Age, and Sex

It is not without interest to compare now the fluidities and hemoglobin values of healthy persons of both sexes and all ages, during the hours of the day, using the data of Blunschy, Table VIII.

From the very limited data available certain provisional conclusions may be reached. From birth to 10 years the hemoglobin is low and the fluidity high. From 14 years on, the fluidity of the blood of men is on the average appreciably constant, whereas the fluidity for women is higher until after the menopause, when it is approximately the same as for men. This change is due to a rise in hemoglobin occurring after the menopause. Particularly on this point additional data are needed.

Six persons were tested by Blunschy over the waking hours of a day, two men and four women. The first test was at 7:30 followed by breakfast (B) at 8:00; they were tested again at 11:00 before lunch (L) at 12:00 M. They were again tested at 1:30 and 3:00. They were served coffee (C) apparently at 3:30 and another test was made at 4:00. A test was made at 6:00 before supper (S) at

6:30 and the final test was made at 9:00. The results for the different individuals vary but they are in general agreement, the averages only being given in Table IX.

TABLE VIII

The Relation of Fluidity to Time of Day, Age, and Sex

After Blunschy (2).

	Age in years							
	0–9.9	10–13.9	14–19.9	20–29.9	30–39.9	40–49.9	50–59.9	60–
	Fluidity							
	39.2	—	35.1	35.5	33.9	35.1	32.7	31.2
Women	Hemoglobin							
	64	—	75	77.5	83	76	85	90
	No. of cases							
17	0	0	1	4	3	4	1	1
	Fluidity							
	37.5	34.0	33.7	31.4	30.7	29.5	31.0	31.2
Men	Hemoglobin							
	65	78	77	90	91	97	86	88
	No. of cases							
55	6	2	6	21	11	4	2	3

TABLE IX

The Change of Fluidity of the Blood with the Hours of the Day

After Blunschy (2).

	A. M.				P. M.							
Hours........	7:30	B	9:00	11:00	L	1:30	3:00	C	4:00	6:00	S	9:00
Fluidity, *rhes*......	29.6		31.9	31.5		33.0	32.2		32.4	32.5		32.2

It was observed by Blunschy that on rising, "*Aufstehen,*" the fluidity was invariably lower by about 10 per cent, which does not take place when persons remain in bed. This has not been explained, but with the increased activity of the heart on rising one is inclined to inquire as to the possible chemical reduction of the blood causing the swelling of the red blood cells.

During the night the blood shows a marked loss in fluidity due perhaps partly to dehydration and perhaps partly to lowered respiration and aeration when reclining. At any rate the marked rise in fluidity which uniformly occurs after arising, averaging 10 per cent, is worthy of note. Arising in the morning changes the bodily tempo, it causes changes in hydrostatic pressure which may cause a certain amount of seepage of liquid into the tissues, and thus affect the concentration of the blood, but this seems of less importance. With breakfast the fluidity rises and then falls, with lunch it again rises and falls. It is not evident whether the fluidity rises and falls after supper or not.

Dehydration of the Blood

The fluidity of the blood follows a somewhat zigzag course during the day, the fluidity being increased after meals according to Burton-Opitz (10), Bence (11), and Breitner (12). We will again cite an experiment of Blunschy. After breakfast at 10:00 a.m. five persons were tested and then again at 11:30 a.m. There was during this period a loss of fluidity of 2.2 per cent. They were then served lunch but without soup or beverage and at 12:45 again tested, when the fluidity of the blood of each had increased, the average increase being 7.5 per cent. It may be argued that since food contains a very high percentage of water or the elements of water these facts may be explained by the hydration of the blood. It is not so easy to explain why warm water increases the fluidity more than cold water and beer is without effect. The fluidity of the blood is due to the water present, but the body is able to excrete any excess of water, therefore we may well hesitate to reach conclusions from scanty data until the condition of hydration of the blood is known. The blood is almost certainly dehydrated in the morning on rising, hence it is significant that there should invariably be a rise in fluidity after breakfast. It is of little importance that it turns out that later in the day when the blood is normally hydrated, the drinking of beer is without effect, on the fluidity. Blunschy found that in 12 cases the diuretic, caffeine, caused a lowering of the fluidity of the blood, without exception.

Blunschy found the effects of work also somewhat contradictory. Five persons engaged in the heavy work of cleaning a floor with steel wool from 2:00 to 3:15 p.m., perspiring profusely, and becoming very tired. In each case the blood showed a loss in fluidity, with an average loss of 4.6 per cent. Five young men, on the other hand, were out all day on a ski trip ascending to 1500 meters, and the final test was made on returning when they had not eaten for 5 hours. The fluidity of the blood of each showed an increase, the average being nearly 13 per cent. They perspired profusely but no report is made of the amount of liquid taken in, but the elevation and the cold mountain air are factors which should be considered.

Poiseuille (13) noted that alcohol added to serum increases its viscosity and it does the same when injected into the blood stream of animals. Nevertheless, cognac administered to fourteen young men was found by Blunschy to raise the fluidity in every case save one, with an average of 5 per cent. In this case also there is then an apparent contradiction.

Relative to the importance of the water reserve of the body, Cannon (14) quotes Rubner to the effect that through fasting, one may lose practically all of his stored glycogen, without any noteworthy consequences, all of his reserve of fat, and one-half of the protein which is either stored or built into the body structure and yet not be confronted with great danger. On the other hand, the loss of only 10 per cent of the body water is serious and a loss of from 20 to 22 per cent means certain death. In other words, while the body contains some 45 kilos of water on the average, the loss of only 5 kilos of water is fraught with danger although that is scarcely as much as the weight of the blood itself (5.5) and a loss of water which is twice that of the weight of the blood cannot be tolerated. This very impressive fact seems to have stimulated little research commensurate with its importance.

Dehydration of the body occurs under a variety of conditions, some pathological as in nausea, diarrhea, cholera, etc., others not pathological as in the case of severe burns or famishing on sea or land. Czerny (15) in 1894 observed the thickening of the blood of cats kept in a warm room without water. He noted the increase in corpuscles and suggested that death was due to the increase in viscosity of the blood. The paste-like consistency of the blood of the ill-fated passengers of the dirigible Hindenburg was noted.

Baths

Considerable attention has been devoted to the supposed or real effects of sweating in various types of baths. Müller (16) claimed that air-baths caused an increase in the viscosity of the blood with an increase in blood pressure (18). Both Kundig (17) and Lommel (18) failed to confirm these claims. But decisive experiments would require further information such as the state of hydration at the beginning, the loss of weight during the experiment, etc.

Stasis

The stoppage of the flow of blood, as by tying, invariably produces a considerable decrease in the fluidity of the blood. There is an increase in the hemoglobin content presumably due to the diffusion of the serum through the walls of the capillaries, which may be thought of as "leaky" tubes. But calculation of the fluidity expected for the given hemoglobin content shows that the fluidity is very much lower than can be explained by it alone. The stasis results in a drop in the pH of the blood due to the accumulation of carbon dioxide. The carbon dioxide causes a swelling of the erythrocytes and a lowering of the fluidity. On the other hand, aeration of the blood causes changes to take place which are the reverse of these, with a decrease in the fluidity of the blood, so even in taking samples of blood for test care must be taken to avoid stasis and also a separation of blood cells from plasma. Two observations of Blunschy on stasis are given in Table X.

It is in harmony with the above, that venous blood has a higher volume of blood corpuscles than the arterial but a lower fluidity.

Bleeding

The effects of loss of blood in surgical operations, venesection, or from wounds have been studied by Müller (19), Oelecker (20), and others. In artificially restoring the volume to the blood, it is necessary to maintain a certain viscosity, by adding proteins as well as physiological saline solution, and most effectively by the use of blood plasma. This subject is one needing much study. The cause of the fall in fluidity with subsequent rise on venesection seems not to be fully explained.

TABLE X

The Effect of Stasis in a Blood Vessel

Subject	Before stasis				After stasis			
	η obs.	H obs.	Φ obs.	Φ calc. equation (1)	η obs.	H obs.	Φ obs.	Φ calc. equation (1)
M. B.........	4.70	80	30.6	33.8	8.9	112	16.2	26.1
A. B.........	3.94	70	36.5	36.2	6.4	90	22.8	31.4

From experiments with over two hundred patients Müller concluded that the normal operation produced first a fall in fluidity in the post-operative phase, then a slower rise during the exhaustion phase in which the fluidity would rise above normal, followed by a gradual return to normal in the recovery phase. All of these changes he found to go parallel with the number of erythrocytes present in the blood as indicated elsewhere in this paper. He also proved that the fluidity of the serum was not altered. When, however, the fluidity of the blood of the patient had been greatly altered by disease, the above sequence of events might be altered thereby.

Air Pressure

Both men and other animals when subjected to changes in external air pressure for considerable periods, require acclimatization involving profound changes in the blood. According to Krogh (21), when one goes to a high altitude there is a quite immediate concentration of hemoglobin, (*cf.* Oti (22)) brought about by removal of plasma but there is subsequently a slow increase in the absolute amount of hemoglobin. If the change of environment is made early enough in life, this increase may be adequate and without injury to normal life processes, but if made late in life, it may be necessary to change periodically to the former environment, thus proving that the acclimatization is far from complete. This subject will become of greater interest perhaps as aviation in the stratosphere becomes more common.

If it is true that men doing heavy work and athletes and soldiers called upon for sudden and extreme exertion demand more meat in their diet than do women and others doing light work, we find an explanation in the higher hemoglobin content of the blood in the former, since hemoglobin is produced in the body by eating meat, particularly liver. This raises the question as to whether persons with a high hemoglobin content of the blood can be better acclimated to high altitudes.

It appears axiomatic that the blood is as fluid as possible without loss of efficiency, because unnecessary viscosity means added work for the heart. This might indicate that women and children and even men doing light work possess a certain advantage if their normal hemoglobin content is low. But it has to be remembered that the circulatory system is more than for transportation solely; the blood is also a reservoir, since the plasma diffuses quite freely into the *milieux interne*. Thus the body is nourished and the lymph gives suppleness and softness to the tissues and skin. The proteins play an important rôle in the flow by osmosis through the intestinal walls, in the kidneys and elsewhere, maintaining the homeostasis of water in the blood. Thus the acclimatization of the animal to a new environment is not a simple matter.

Comparison of the Blood of Other Animals

There have been many measurements of the viscosity of the blood of the lower animals, but recently Rhiel (23) has reviewed the earlier data and made a systematic study of six species of animals, using ten individuals (five male and five female) of each species, measuring the viscosity of the whole blood, the plasma and serum as well, and the hemoglobin content. We will not attempt a detailed discussion, but such ample data make some inferences desirable.

In every species, different individuals exhibit variations of fluidity and hemoglobin content which are wide as compared with man. The average values given in Table XI, show that the blood of rabbits (I) is distinctly more fluid and that of pigs (VI) less fluid than that of the other species and in the following general order: rabbits (I), goats (II), horses (III), sheep (IV), cattle (V), and pigs (VI). Genetically the rabbit is a rodent and the others ungulates, but all are mammals and all herbivorous except the pig which is omnivorous like man. It is therefore of interest that on the basis of both fluidity and hemoglobin content men are situated between pigs and cattle. We are sorry not to include data on carnivores, birds, reptiles, and amphibians.

In each species with the exception of goats, the mean hemoglobin content of the blood was higher in the case of the males than of the females as in man; and in every species with the sole exception of rabbits a high mean hemoglobin content corresponded to a low mean fluidity, as we have found to be the case with individual men and women. To bring this out very clearly, all of the observations were first arranged in the order of increasing fluidity. The data were divided into decades and the number of individuals in each species noted for

TABLE XI

The Mean Fluidities at 37° of the Whole Blood of Different Species and Sexes of Mammals with Values Calculated from the Hemoglobin Content of Rhiel Using Formula $\Phi = \Phi_1 - bH$

Animal	Sex	H obs.	Φ obs.	Φ calc.	Φ_1	b	Deviation
							per cent
Rabbits	♂	11.98	42.0	34.6			
I	♀	11.72	41.3	41.6			
	Average......	11.86	41.6	34.8	52.6	0.92	4.4
Goats	♂	10.73	37.8	37.1			
II	♀	11.01	35.4	36.5			
	Average......	10.87	36.6	36.8	57.6	1.93	5.5
Horses	♂	11.96	34.0	34.6			
III	♀	11.01	36.7	36.5			
	Average......	11.48	35.4	35.6	37.6	0.19	10.8
Sheep	♂	12.37	33.2	33.8			
IV	♀	11.25	35.3	36.0			
	Average......	11.81	34.2	34.9	73.8	3.35	9.5
Cattle	♂	12.55	31.1	33.4			
V	♀	10.94	31.7	37.7			
	Average......	11.74	31.4	35.0	43.2	1.00	4.4
Pigs	♂	16.21	23.6	36.1			
VI	♀	15.71	25.1	37.1			
	Average......	15.96	24.4	26.6	63.4	2.44	5.4

every decade as given in Table XII and the mean position for each species was calculated, which is given in the final column. It is noted that the species seem about equally separated from each other, but the separation of rabbits from the others is marked. Then the same operation was repeated except that the data were arranged on the basis of increasing hemoglobin content (Table XIII); it is seen that the mean values increase in the reverse direction now with the exception of rabbits (I), if we neglect the practical equality of (III) and (IV). The anomaly afforded by rabbits needs explanation.

There may be no apparent reason why equation (1) should apply to two in-

TABLE XII*

The Grouping of Animals When Arranged by Decades according to the Fluidity of the Whole Blood

Data of Rhiel (23).

	0–10	10–20	20–30	30–40	40–50	50–60	Mean
I	8	2	—	—	—	—	0.7
II	2	2	3	3	—	—	2.2
III	—	4	3	—	3	—	2.7
IV	—	2	1	4	2	1	3.4
V	—	—	2	3	3	2	4.0
VI	—	—	1	—	2	7	5.0

*The heavy bars in Tables XII and XIII are placed according to the printer's *ems* given in decades at the head of the tables thus representing the mean values for each type. One may get a graphical idea of the facts by imagining a curve drawn through the middle of the bars in succession.

TABLE XIII

The Grouping of Animals Arranged according to the Hemoglobin Content

Data of Rhiel (23).

	0–10	10–20	20–30	30–40	40–50	50–60	Mean
I	—	4	1	3	2	—	2.8
II	—	1	1	—	4	4	4.4
III	—	—	4	2	2	2	3.7
IV	—	1	1	4	2	2	3.8
V	1	3	3	1	—	2	2.7
VI	9	1	—	—	—	—	0.6

dividuals of the same species and therefore much less reason for individuals of different species unless corpuscles of similar shape and size do lower the fluidity of plasma in the same manner. This is a large subject and the data are still inadequate. We have, however, worked out constants for the equation

$$\Phi = \Phi_1 - b\,H \qquad (3)$$

as given in the Table XI. The average percentage deviation between the observed and calculated values using these equations is 6.7 which is just twice that obtained with healthy men and equation (1). The average value of Φ_1 is 54.7 which cannot be distinguished from the 53 found for human blood. Applying the same type equation to the entire data, the percentage of error rose to 11 per cent. The equation used was $\Phi = 58.5 - 0.20\,H$, the values of H being not the Sahli values used by Blunschy and Bolle.

SUMMARY

In the preceding paper (1*b*) a formula was developed for the lowering of the fluidity of a medium by a mixture of proteins, given the volume concentration of each and its fluidity-lowering constant. Whole blood is now shown to follow an essentially similar formula, except that the hemoglobin content is taken from the literature as the best available measure of the volume of the blood cells $\Delta\,\Phi = 0.24H$, assuming the fluidity of the medium to be 53 rhes. Age, sex, diet, barometric pressure affect the hemoglobin content of the blood, but the formula may apply to any healthy human blood to about 3 per cent. The shape, number, and size of the blood cells, if known, might help to explain discrepancies as well as the state of oxidation of the blood. In disease the discrepancy becomes much greater, suggesting the possible use of rheology in diagnosis.

BIBLIOGRAPHY

1. Bingham, E. C., and Roepke, R. R., (*a*) *J. Am. Chem. Soc.*, 1942, **64,** 1204, (*b*) *J. Gen. Physiol.*, 1944, **28,** 79.
2. Blunschy, F., Beiträge zur Lehre der Viskosität des Blutes, Inaugural Dissertation, Zurich, Eberle and Rickenbach, 1908.
3. Schukowa-Florensowa, M., Die Viskosität des Blutes der Kinder, besonders der Mundatmer, Inaugural Dissertation, Bern, Kamp-Berger, 1910.
4. Mayers, L. H., The erythrocyte curve at various ages, *Arch. Int. Med.*, 1923, **30,** 478.
5. Bolle, B., Beitrag zur Kenntnis der Viskosität des Blutes, des Serums und des Plasmas, Inaugural Dissertation, Berlin, Gustav Schade, 1909.
6. Reiss, E., *Ergebn. inn. Med. u. Kinderheilk.*, 1913, **10,** 532.
7. Schorer, G., *Cor.-Bl. schweiz. Aerzte*, 1913, **43,** 1523.
8. Heyder, E., Bestimmungen der Refraktion und Viskosität von Globulinen und Albuminen in ihren Mischungen nach verschiedenen Verhältnissen, Inaugural Dissertation, Tübingen, Landseidel in Cassel, 1915.
9. Nägeli, O., Blutkrankheiten und Blutdiagnostik, 4th edition, Julius Springer, Berlin. *Cf.* chapter on the viscosity of the blood.
10. Burton-Opitz, R., *Arch. ges. Physiol.*, 1900, **82,** 447.
11. Bence, J., *Deutsch. chem. Woch.* 1905, **58,** 203.
12. Breitner, J., *Folia haematol.*, 1905, **2,** 448 (abstr.).

13. Poiseuille, J. M. L., Study of the causes of the movement of the blood in vascular capillaries, *Ann. chim. pharm.*, 1848, **64,** 129. *Compt. rend. Acad.*, 1843, **16,** 60.
14. Cannon, W. B., The wisdom of the human body, New York, Norton and Co. 1932.
15. Czerny, *Arch. exp. Path. u. Pharmakol.* 1894, **34,** 268.
16. Müller, W., *Zentr. Chir.*, 1909, **36,** 1401.
17. Kündig, H., Über die Viskosität des menschlichen Blutes bei Schwitz Brozeduren, Inaugural Dissertation, Jena, Frommann, 1903.
18. Lommel, *Deutsch. Arch. klin. Med.* 1904, **80,** 308.
19. Müller, O., On the effect of baths and douches on the blood pressure, *Deutsch. Arch. klin. Med.*, 1902, **74,** 316.
20. Oelecker, F., *Berl. klin. Woch.*, 1910, **97,** 578.
21. Krogh, A, The anatomy and physiology of the capillaries, New Haven, 1929.
22. Oti, Y., *Okayama Igakkai Zassie*, 1940, **52,** 1404. *Cf. Chem Abstr.*, 1943, **37,** 1749. Frogs at an air pressure of 300 mm. show an increase in hemoglobin of 9.9 per cent in one hour.
23. Rhiel, *Arch. ges. Physiol.*, 1943, **246,** 709.